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Behavior, damage and fatigue life assessment of lost foam casting aluminum alloys under thermo-mechanical fatigue conditions

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Abstract

The purpose of this paper is to define a thermomechanical fatigue criterion in order to predict the failure of the cylinder heads issued with the lost foam casting process. The microstructure of the materials (A356-A319) is affected by the lost foam casting process which can directly affect the mechanical properties, the damage mechanisms and thefatigue failure of the materials. The major problem in defining a predictive fatigue criterion in this case is the fact that it should be on one side applicable for the structure which is submitted to complex multiaxial thermomechanical loadings and on the other side should take into account the microstructural effects of casting process.

Keywords: thermomechanical fatigue; Al-Si-Mg alloys; lost foam casting.

1. Introduction

Gravity cast aluminum alloys are widely used for cylinder head application in the automotive industry because of their good cast ability, physical and mechanical properties. Recently due to process cost reduction goals, conventional die casting process (CD) is being replaced by lost foam casting process (LFC) that has not been extensively characterized under fatigue loadings while cylinder head is subjected to thermomechanical loading cycles during the operation of engine.

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Nomenclature

$\Delta\sigma_{tmax}$	maximum stress range of a cycle	$\varepsilon°$	rate of mechanical strain
E	elastic modulus	σ_{max}	maximum stress of a cycle
ε_p	plastic strain range	$\Sigma_{h,\max}$	maximum hydrostatic pressure
$\Delta\varepsilon$	mechanical strain range	$\Delta\sigma$	stress range
ΔW_t	total energy	$N_{simulated}$	estimated fatigue lifetime
ΔW_p	dissipated plastic energy	$N_{experimental}$	experimental fatigue lifetime
ΔW_e	elastic energy	A, c, n, K, α	material constants

The prediction of fatigue life and failure of structures is one of the main problems in mechanical engineering and has been the subject of major efforts in the last few decades. There are some difficulties in attaining this objective. One of these difficulties is to dispose a robust criterion at the microscopic level to predict low cycle thermomechanical fatigue failure of structures. The fatigue failure criterion should predict the lifetime of both isothermal and anisothermal low cycle fatigue, in a large range of temperatures and loadings [1].

This work is focused on the cylinder heads made of A356 and A319 alloys which issued with LFC process. The SEM (Scanning Electron Microscopy) observations show that the microstructure of these materials will extremely change after LFC process. The microstructure of the material can widely affect the mechanical properties, damage mechanisms and the fatigue failure. The aim of this work is thus to study the effects of casting process on the mechanical properties, damage mechanisms and the fatigue failure. Low Cycle fatigue (LCF) and ThermoMechanical Fatigue (TMF) tests were provided to reach these objectives. The damage mechanisms of the specimens after the fatigue tests were studied. After an interpretation of the tests results using different criteria, it is shown that Koh and Haddar's approaches seem to be well adapted to these materials lifetime prediction.

2. Materials and Microstructure

2.1. Lost foam Casting

Lost foam Casting (LFC) is a relatively new process begins with a Styrofoam assembly that replicates the part being cast. Loose sand is poured around the assembly and shaken into its voids. Molten aluminum is then poured through foam placed into the sand where the hot metal melts the foam, displaces it and cools in the shape of the part.
Recently due to process cost reduction goals, conventional DC process is being replaced by LFC process. A major specificity of LFC is the fact that the cooling rate of the process is relatively slow in compare with DC process (LFC around 0.8 °C/s and DC around 30 °C/s) [2]. The difference in cooling rate will create a coarser microstructure when measured in term of DAS. Beside, the porosity and inclusions (intermetallics, oxides) are increased and clustered. All of these phenamena can significantly reduce overall mechanical properties and the component life. (Figure 1)

2.2 Materials

The alloys studied next are two aluminum-silicon alloys of the automotive industry: A356 with T7 heat treatment and A319 without heat treatment. We will focus essentially on the LFC process. The over-aging has been determined by stabilization both in mechanical properties and microstructure of the material. In our case the over-aged condition corresponds to the heating of material at 250°C for 200 hours. A356 and A319 were studied in non-aged and over-aged conditions.

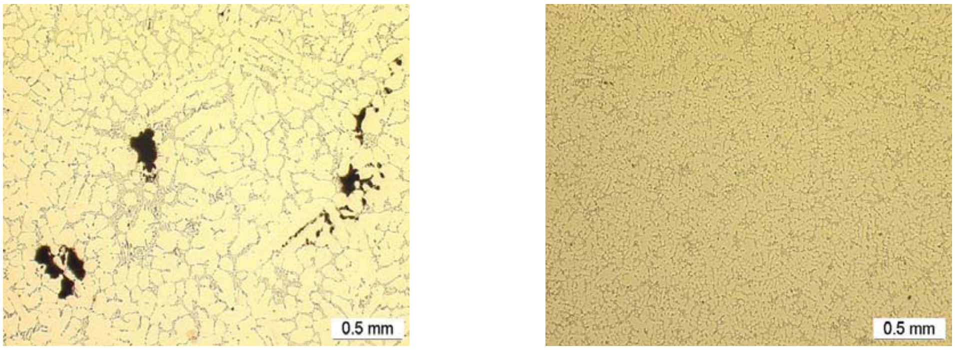

Fig. 1. (a) Microstructure of A356 issued with LFC process, DAS: 85µm ; (b) Microstructure of A356 issued with traditional DC process, DAS:35µm

2.3 Microstructure

In order to respect the process details of the critical areas in cylinder heads, we have extracted specimens from the inter-valve areas. For observation on the SEM (Scanning Electron Microscopy) S-3600N HITACHI, the specimens have been polished with 500, 600, 1200 and 2400 grit papers (coarser polishing). Final polishing was carried out with 6, 3 and 1 micron diamond pastes (fine polishing). Figures 2 and 3 represent the microstructure of LFC A356 and A319.

The materials focused on, are containing silicon with magnesium and/or copper. These elements cause the formation of specific intermetallics phases. Iron, magnesium and copper containing intermetallics were found in the microstructure of A356 and A319. Iron-containing intermetallics phases are the most common among the three and are sometimes deleterious to mechanical properties. Two pre-eutectic iron-containing intermetallics that we recognized in the microstructure are α-AlFeSi and β-AlFeSi. [3, 4]

α-AlFeSi phase can be found with different compositions and morphologies; they depend on the quantity of "iron correcting" elements, such as Mn and Cr and mostly with the morphology that is called "Chinese script" or script phase. β-AlFeSi phase is the critical intermetallic compound to focus on when analyzing A356 alloy. It has a destructive effect on ductility and fracture toughness. This phase is found along grain boundaries and has a detrimental needle-like morphology. Mg and Cr are "iron correcting" elements because they reduce the amount of α-AlFeSi phase and form a less harmful β-AlFeSi. It has been observed that as the cooling rate decreases in lost foam casting, the β-AlFeSi phase increases in length and thereby destroying some mechanical properties [5].

Si particles which are introduced into the aluminum matrix primarily to improve castability and the flowability, another significant precipitation appears as thin plate-like structures (acicular). The morphology of the silicon is quite dependent on the cooling rate. With low cooling rates in lost foam casing, silicon appears coarser [2].

All copper base intermetallics in aluminum alloys crystallize at the end of solidification in the remaining inter denendritic liquid. Θ-Al_2Cu phase appears in A319 as eutectic pockets intermixed with the aluminum matrix. [6, 7]

β'-Mg_2Si phase which has small black script morphology develops in the final stages of solidification of A356 at very high cooling rates. Due to the low cooling rate of LFC, not lots of β'-Mg_2Si phases were observed in the microstructure.

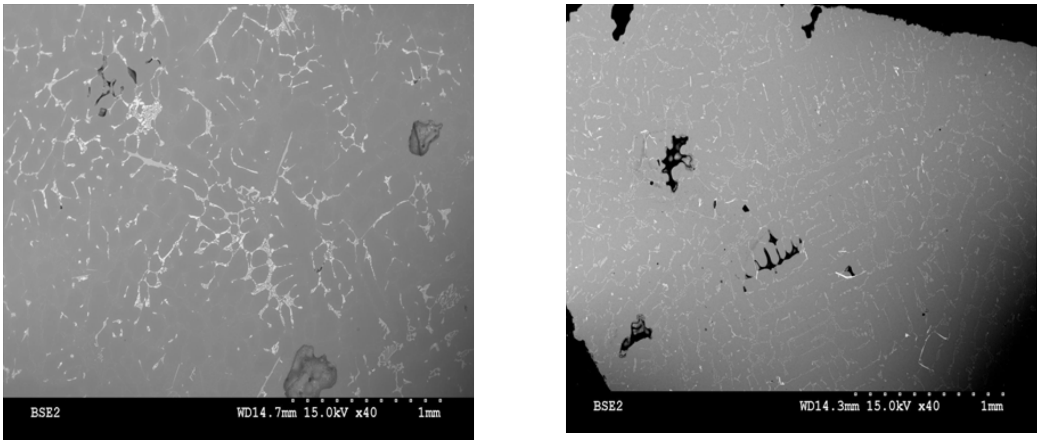

Fig. 2. (a) Initial microstructure of LFC A319; (b) Initial microstructure of LFC A356

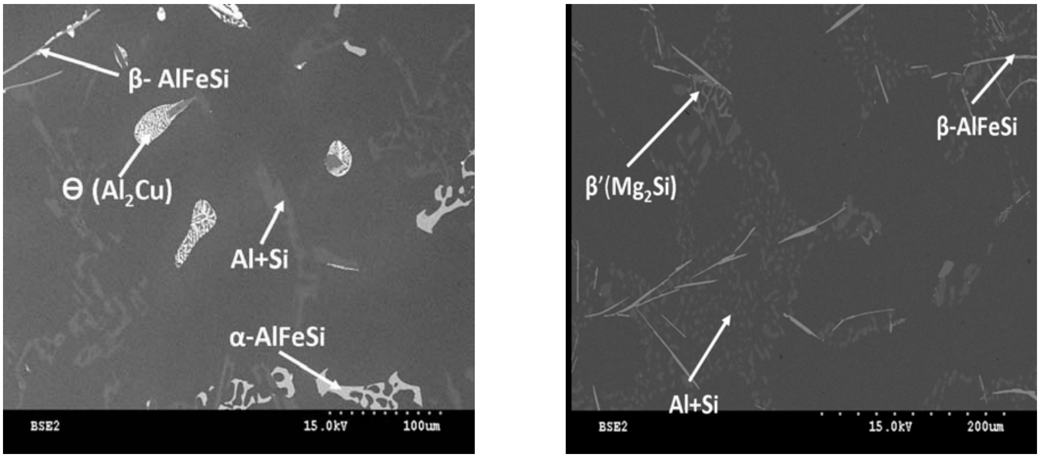

Fig. 3 (a) Initial microstructure of LFC A319 ; (b) Initial microstructure LFC A356

SEM observations in figures 4 and 5 represent the non-aged and over-aged A319 and A356. Not any significant difference was noticed in term of DAS and intermetallics size of A319. β-AlFeSi phases seem to increase slowly after the aging, but not important changing in term of DAS and intermetallics size.

3. Cyclic mechanical behavior

Strain controlled LCF (Low Cycle Fatigue) and TMF (Thermo Mechanical Fatigue) tests were performed to determine the cyclic mechanical properties, fatigue lifetime and damage analysis of lost foam materials.

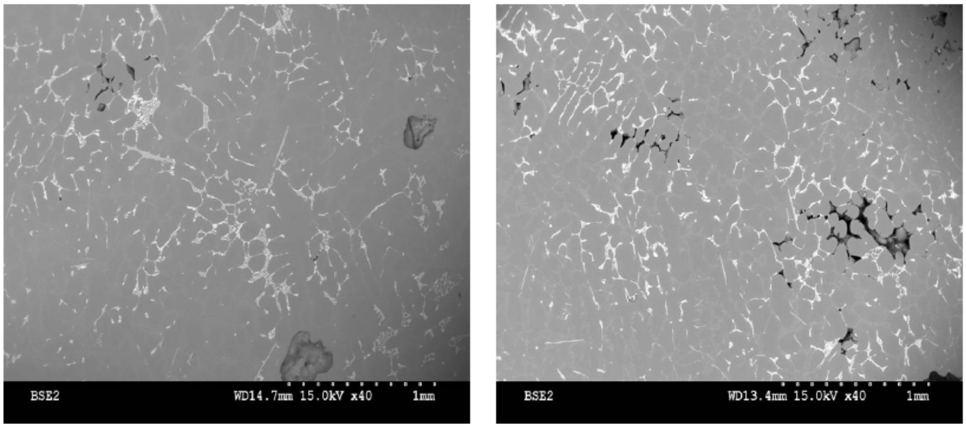

Fig. 4 (a) Initial microstructure of LFC A319; (b) microstructure of LFC A319 after 200 hours of aging at 250°C (over-aged condition)

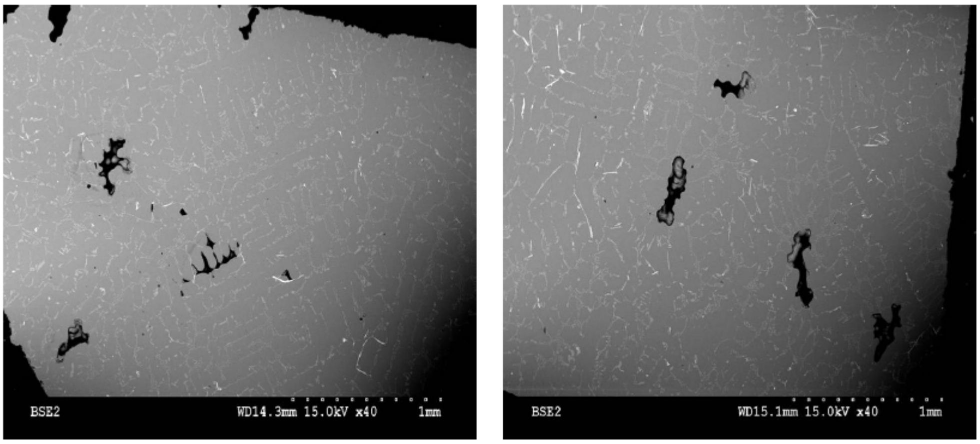

Fig. 5 (a) Initial microstructure of LFC A356 ; (b) microstructure of LFC A356 after 200 hours of aging at 250°C (over-aged condition)

3.1 Tests procedures

Both TMF and LCF tests were performed with a mechanical strain ratio (R_ε=-1) and a mechanical stain rate of $\varepsilon°=10^{-3}$(1/sec). LCF tests were carried out at 250°C for the variable mechanical strain range (Δε%=0.2-0.8). Out-of-phase TMF tests were conducted with cyclic temperature between 100°C-250°C and variable mechanical strain range (Δε %=0.2-0.8). Figure 6 compares the fatigue lifetimes of LFC A319 and A356 in non-aged and over-aged conditions. Fatigue lifetime is defined as sudden 10% drop of maximal stress, before the fracture of the specimen. The experimental results show that the non-aged A356 has a sudden fall of maximum stress in a few first cycles. It seems that A356 softens in the first cycles and then get to the stabilized state. A319 softens slowly and get to stabilized state later than A356. ϴ-Al_2Cu phases retain the hardening effects at high temperatures, this fact can be the reason of slow stabilization of A319 [8]. In this study the over-aged material supposed as a reference material for mechanical properties and microstructure. The cyclic behaviors of A319 and A356 were also represented in figure 6 at the fatigue midlife time and the stress is divided by the initial stress obtained in the over-aged state. In different aging condition and casting process, the yield strength of A319 is always superior in compare with A356. Comparison of cyclic behaviors of the LFC and DC materials shows that the casting process can not affect the cyclic mechanical behaviors of materials.

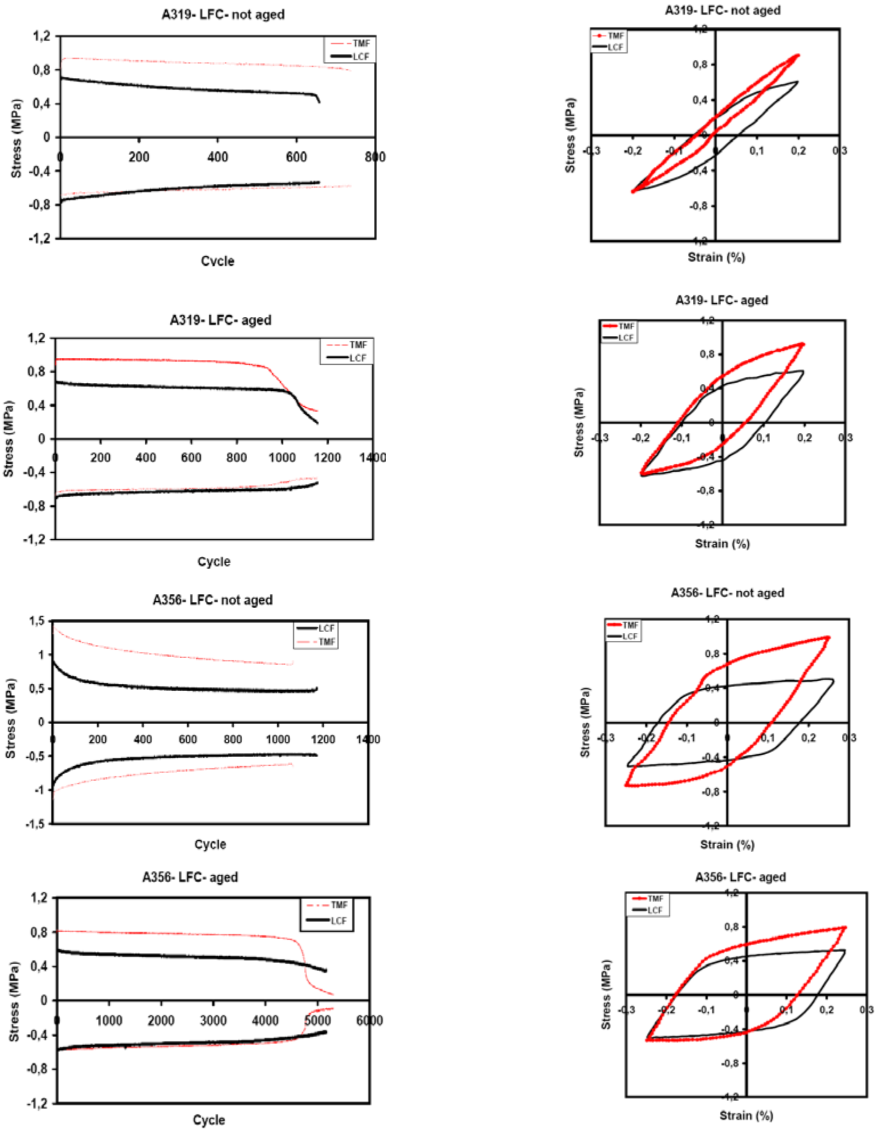

Fig. 6 (a) fatigue lifetimes comparison of TMF-LCF test for non-aged A319; (b) cyclic behaviors comparison of TMF-LCF test for non-aged A319; (c) fatigue lifetimes comparison of TMF-LCF test for aged A319; (d) cyclic behaviors comparison of TMF-LCF test for aged A319; (e) fatigue lifetimes comparison of TMF-LCF test for non-aged A356; (f) cyclic behaviors comparison of TMF-LCF test for non-aged A356; (g) fatigue lifetimes comparison of TMF-LCF test for aged A356; (h) cyclic behaviors comparison of TMF-LCF test for aged A356.

4. Damage and fatigue lifetime analysis

4.1 Damage analysis

The fracture surfaces of failed specimens under LCF tests were assessed by means of SEM observations. Figure 7 (a) shows that DC A356 has plenty of cup-cons on the fractured surface. These cup-cons are due to the ductile fracture in DC materials [9]. Figures 7 (b) and 7 (c) represent LFC A356 and A319 with plenty of micro cracks, in particular on the boundary cells and inside the eutectic phases. A concentration of the micro cracks was observed inside the intermetallic phases, especially β-AlFeSi and ϴ-Al2Cu phases. The initiation of micro cracks or the dominant crack (main crack) were not recognized, but the fracture surfaces revealed that the initiation of the first micro cracks generally occurred near the micro porosities and propagated toward the β-AlFeSi and ϴ-Al2Cu interemetallic phases. The concentration of internal stresses over the intermetallic phases certainly causes the sudden rupture of these materials [10].

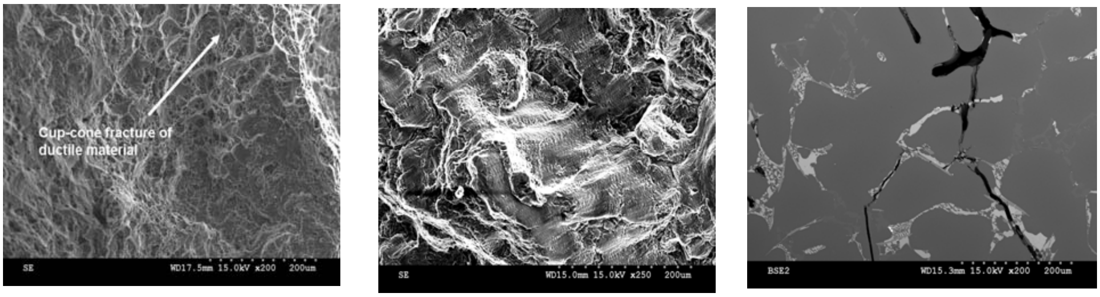

Fig. 7 (a) Cup-cons of ductile rupture in DC A356 after LCF test at 200°C, Δε%=0.8 ; (b) Cracks in cells boundaries in LFC A356 after LCF test at 200°C, Δε%=0.8; (c) Micro cracks in the eutectic phases in LFC A319 after LCF test at 250°C, Δε%=0.8

4.2 Fatigue lifetime analysis

Fatigue lifetimes of LFC and DC A319, were compared in figure 8, in LCF test (Δε%=0.6) at 250°C. This figure shows that the fatigue lifetime of LFC A319 decreases drastically. Casting process can affect the fatigue failure of this material severely. As mentioned before the casting process can not affect the cyclic mechanical behaviors of the material but it can change the damage phenomena. Therefore, it is important to define an indicator which is related to the damage in order to explain the fatigue lifetimes of LFC materials. The experimental results show that the difference of fatigue lifetime in the case of A356 LFC and DC is not as severe as in A319.
To demonstrate the effects of the material composition on the fatigue failure, A319 and A356 were compared together for the same casting process. These comparisons show a short fatigue life in LFC A319 in compare with LFC A356, for the same mechanical strain range.

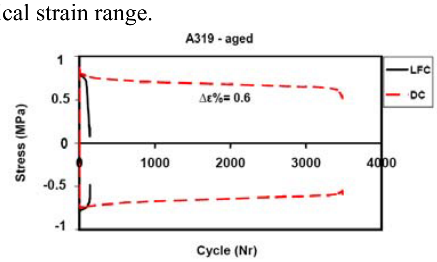

Fig. 8 fatigue lifetime comparison between A319 LFC and A319 DC, LCF test (Δε%=0.6 at 250°C)

4.3 Comparison of fatigue criterions

Past efforts [11, 12] show that the cumulative plastic strain energy can be an efficient criterion for fatigue lifetime assessment. This criterion quantitatively relates the fatigue properties of a material to its cyclic stress-strain properties. The plastic strain energy is equal to the area inside the stabilized strain-stress hysteresis loop (equation 1).

$$\Delta w_p = \int_{cycle} \underline{\underline{\sigma}} : \underline{\underline{\dot{\varepsilon}}}_p \, dt \quad (1)$$

However, as shown before, the LFC process strongly affects the microstructure of the material. The presence of many intermetallic phases in the matrix intensifies the hydrostatic pressure effects which can be described by the spherical part of the energy. A correction is needed for the hydrostatic part which is not captured by the plastic dissipated energy which is only deviatoric. This part will also correct for the mean stress and triaxiality effects. A proposal has been given by Amiable [13]. This criterion defines a function (Φ) involving the maximum hydrostatic pressure with the cumulative plastic energy as follow in equation 2. α is a material constant.

$$\Phi = \Delta w_p + \alpha.\Sigma_{h,\max} \quad (2)$$

Other similar fatigue criteria were proposed by Haddar et al [14] and Koh [15]. These criteria integrate the hydrostatic part, by calculating the elastic energy in two different ways. In Haddar criterion the total energy and the fatigue lifetime are calculated as follow, represented in equation 3 and 4. A and c are the material constants:

$$\Delta w_t = \Delta w_p + \Delta w_e = \frac{\Delta\sigma^2}{E} + \Delta\sigma.\Delta\varepsilon \quad (3)$$

$$\Delta w_t = AN^{-C} \quad (4)$$

Koh criterion is defined as follow:

$$\Delta w_e = \begin{cases} \dfrac{\sigma_{\max}{}^2}{2E} & for \quad \sigma_{\min} \leq 0 \\ \dfrac{(\sigma_{\max} - \sigma_{\min})^2}{2E} & for \quad \sigma_{\min} > 0 \end{cases} \quad (5)$$

$$\Delta w_t = f(N_f) = A(N_f)^{\alpha} \quad (6)$$

Figures 9 (a), 9 (b) and 9 (c) represent the simulated fatigue lifetime in function of experimental fatigue lifetime in LCF tests for the three criterions: cumulative plastic energy, Haddar and Koh. The standard deviation between the experimental fatigue lifetime and the simulated fatigue lifetime was calculated for each criterion and its value is approximately 71 for Haddar criterion, 76 for Koh criterion and 118 for the dissipated energy criterion. Therefore, Haddar and Koh criteria seem to be the more convenient in our case. It shows that a combination between dissipated energy and stress allows to take into account the influence of local damage in a ductile metallic matrix.

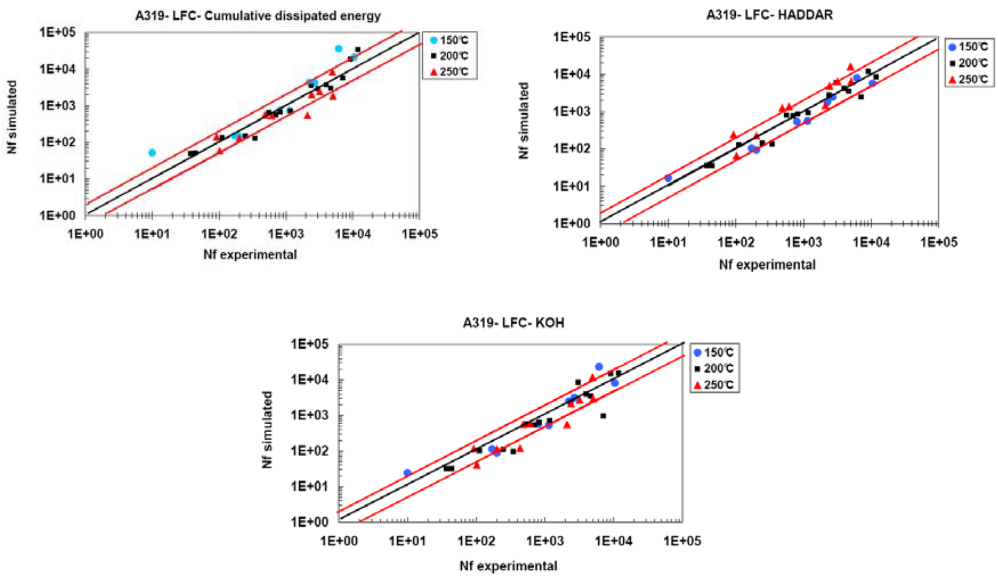

Fig. 9 simulated fatigue lifetime in function of experimental fatigue lifetime (a) cumulative plastic dissipated energy criterion; (b) Haddar criterion (c) Koh criterion

5. Conclusion

The purpose of this paper was to study the mechanical properties, damage mechanisms and the fatigue lifetime of A356 and A319 alloys used in cylinder heads issued with lost foam casting process. The SEM observations showed the differences in term of initial microstructure between A356 and A319. LCF-TMF test results revealed the different cyclic mechanical properties and fatigue failures of the materials: A319 exhibits a higher yield stress in compare with A356 and mechanical properties which seem less ductile in compare with A356.

A significant changing of damage phenomena was noticed by the post mortem SEM observation between A356 and A319 in lost foam process. The observations showed a severe fragile rupture inside the eutectic phases in A319. The ductile rupture with the form of cup cons was appeared in die casting A356.

Finally different thermomechanical fatigue failure criterions based on the LCF-TMF tests were defined to predict the fatigue lifetime of lost foam A319. Haddar and Koh criteria had inferior standard deviation results in term of fatigue lifetime prediction in compare with only dissipated energy based criterion. Incorporating stress in an energetic approach in order to take into account local damage seems to be a promising way in thermomechanical fatigue.

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